Available on CMS information server **CMS CR 2006/064**

CMS Conference Report

19 September 2006

Crystal Properties in the Electromagnetic Calorimeter of CMS

Riccardo Paramatti on behalf of CMS ECAL group

INFN - Rome1

Abstract

The Compact Muon Solenoid (CMS) is a multi-purpose detector for LHC. The electromagnetic calorimeter (ECAL) contains 75848 lead tungstate crystals allowing a very accurate energy measurement of electrons and photons in the GeV - TeV energy range. More than two thirds of the ECAL Barrel has been already assembled.

In this paper an updated analysis on the optical and scintillation properties of about 50000 crystals and an overview on the construction status of the calorimeter are presented. Furthermore, the use of crystal production measurements for the calorimeter precalibration is discussed.

Presented at the XII International Conference on
Calorimetry in High Energy Physics - Calor06
Chicago, USA 5-9 June 2006

1 Introduction

The Large Hadron Collider will allow the study of pp interactions at a center of mass energy of 14 TeV. The main physics goal of the CMS experiment [1], one of the four detectors at LHC, is the quest for Higgs and SUSY particles. The maximum design luminosity foreseen at this machine is 10^{34} cm^{-2} s^{-1} and the crossing rate will be 40 MHz. The production of around 25 events per bunch crossing will result in about 1000 tracks. The radiation environment is expected to be particularly severe. In ten years of running (corresponding to a total integrated luminosity of around 10^6 pb^{-1}) detector parts will be exposed to a maximum neutron fluence of 10^{17} n/cm^2 and γ doses of 10^6 Gy. These extreme conditions have imposed a long R&D phase in order to obtain high granularity, radiation resistant, fast and selective detectors.

The electromagnetic calorimeter of the CMS experiment [2] is composed of 75848 Lead Tungstate crystals organized in a barrel covering the central rapidity region $|\eta| < 1.48$ and two endcaps which extend the coverage up to $|\eta| = 3$. A preshower detector placed in front of the endcaps improves the γ - π^o separation in this region. To increase hermeticity, the barrel has a nearly pointing geometry both in ϕ and η.

In this paper an analysis on the optical properties of more than 50000 CMS crystals produced in Russia by the Bogoroditsk Techno-Chemical Plant is presented.

2 Lead Tungstate Crystals

Lead tungstate ($PbWO_4$) is a very dense (ρ = 8.28 g/cm^3) scintillating material. The most appealing properties of $PbWO_4$ crystals are: the scintillation light decay time (80% of light is emitted within 25 ns), the basic radiation resistance, the small radiation length (X_0 = 0.89 cm) and Molière radius (R_M = 2.2 cm). These properties allow the construction of a compact calorimeter with a granularity suitable for the multiplicity expected at LHC.

Nevertheless this material presents major drawbacks: the low level of light yield (100 photons/MeV, $\sim$ 0.2% with respect to NaI:Tl) imposes a photodetector read-out with internal gain, the strong dependence on temperature of the light yield (-2%/^{o}C around 18 ^{o}C) and the high refractive index (2.29 at peak emission wavelength λ = 420 nm) which makes the light extraction from the crystal very difficult.

During R&D phase (1995-1998), a huge effort was done to improve the light yield of these crystals without spoiling their fast response and to guarantee their radiation hardness at sufficient level to preserve the requested energy resolution.

The $PbWO_4$ crystals show a damage induced by electromagnetic radiation through the creation of color centers that reduce the crystal transparency [3]. The damage, depending on the dose rate, reaches a stable level after a small administered dose. A partial recovery of the crystal transparency happens in few hours. The scintillation mechanism remains untouched and the observed light loss is tolerable and can be followed with a monitoring system by injecting light through the crystals.

2.1 Photodetectors

Avalanche photo-diodes (APD) were developed for the barrel part of the calorimeter. These silicon devices are insensitive to the 4 T magnetic field of the experiment and have an internal gain (M = 50 foreseen for CMS) essential for $PbWO_4$. The quantum efficiency around the wavelength of the $PbWO_4$ emission peak is about 75%-80%. The amplification is obtained in a small region (d_{eff} $\sim$ 6 mm) of high electric field. Two APDs of 25 mm^2 area are coupled to each crystal. In this configuration 4000 photo-electrons per GeV of deposited energy are produced.

In the endcap regions, radiation levels are too high to use APDs; the longitudinal magnetic field allows there the use of vacuum photo-triodes (VPT). These are single stage photo-multiplier tubes with a fine metal grid anode. Their active area is 280 mm^2, quantum efficiency is about 20% at 420 nm and a gain of 10 in the 4 T magnetic field is expected.

3 Construction

The calorimeter construction is a distributed process. The barrel construction started in 2002. Parts, as crystals, capsules, mechanical elements for the support structure etc. are produced under the responsibility of different Institutions taking part to the project and then sent in two Regional Centers located in CERN and Rome.

The calorimeter has a modular structure. The basic sub-unit of the barrel, composed by a crystal (whose dimensions vary with η, being approximately of 2 cm x 2 cm x 23 cm) and a capsule (hosting two APDs read in parallel) glued together, is inserted in a glass fiber alveolar structure. Ten sub-units fit in this structure that is closed by an aluminum tablet and constitute a ”sub-module”. Sub-modules are of 17 different types (as well as crystals) depending on η position. A ”module” is made by 40 or 50 sub-modules mounted on a 3 cm thick aluminum grid. Modules are of 4 η types. A ”super-module” is a set of 4 modules. The barrel consists of two identical halves made by 18 super-modules.

Endcaps will have a simpler structure; 138 ”super-crystals”, each made of 25 crystals, constitute the so-called ”dee” and two dee make an endcap. Endcap crystals are larger with respect to the barrel; the transversal dimensions are $\sim$ 3 cm x 3 cm.

In the Regional Centers, all the elements are assembled and step by step checked, following a well defined quality control protocol. In particular, each crystal is subject to the systematic test of its geometrical shape, longitudinal transmission (related to radiation hardness), transversal transmission, light yield and uniformity of light collection. Both Centers are equipped with similar automatic machines to insure crystal quality. A detailed description of the machines installed in INFN/ENEA and CERN Regional Centers can be found in [4] and [5] respectively. The strict control of quality at each step of the construction will insure a fully operational calorimeter at best of its potentiality and reduce the risk of dead or malfunctioning channels presence. The ”bare” supermodule assembly and its subsequent dressing are done at CERN. Around 75% of the barrel is currently (June 2006) assembled.

4 Optical Properties

4.1 Longitudinal Transmission

The spectrum of transmission along the crystal axis (longitudinal transmission, LT) is measured at different wavelenghts for the acceptance tests of the crystal. In Rome, transmissions are measured through a system of mirrors with a single-beam CCD-diode array spectrophotometer (S2000 from Ocean Optics2) directly coupled to an integrating sphere (Labsphere of 150 mm diameter). Data are taken every 4 nm from 300 to 700 nm. At CERN, transmissions are measured by two separate spectrophotometers using a large area photodiode as detector. The light wavelengths are selected using a set of narrow band pass filters nominally centered at: 330, 340, 350, 360, 380, 405, 420, 450, 492, 620 and 700 nm. The crystal transmittance along its longitudinal axis (LT), in particular around 360 nm, has been proven to be connected with the presence of defects which are correlated with the radiation tolerance of the crystals. Based on this correlation, very strict requirements on the shape and level of the LT were set.

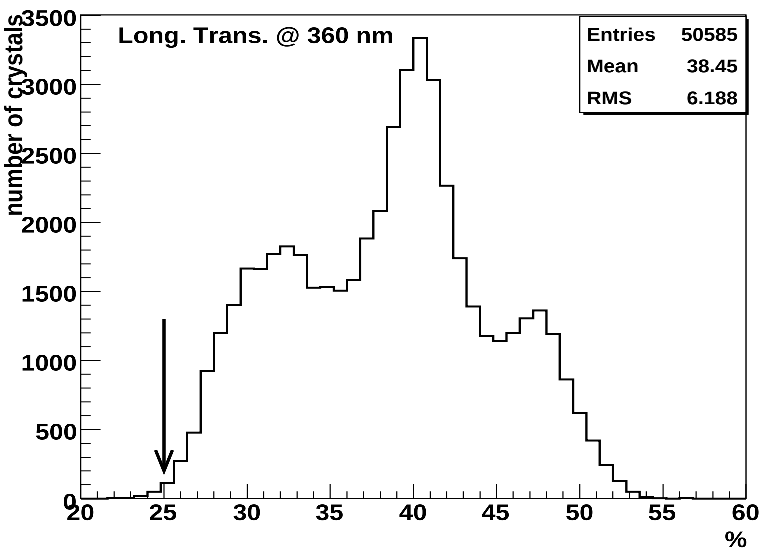

Figure 1: Longitudinal Transmission at 360 nm; the arrow shows the acceptance cut.

In Figures 1 and 2, the distribution of the LT360, LT420 and LT620 measurements are shown together with the acceptance cuts. The higher dispersion of LT360 measurements compared with the others, is due to the extreme sensitivity of the band-edge region to the production conditions. However, this dispersion corresponds to a spread in the edge position of less than 10 nm.

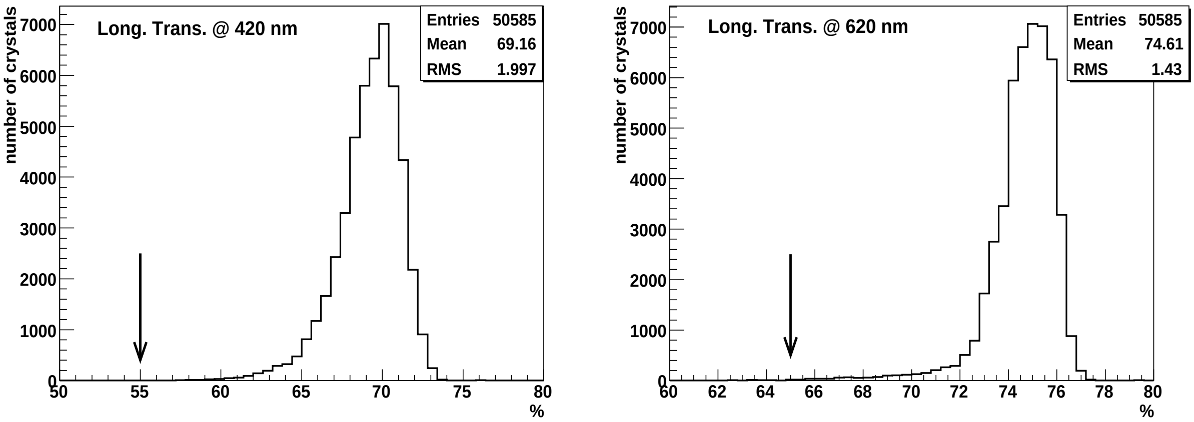

Figure 2: Longitudinal Transmission at 420 nm (left) and at 620 nm (right); the arrows show the acceptance cuts.

4.2 Light yield and front non-Uniformity

The Light Yield (LY) is important for its contribution to the stochastic term of the energy resolution of the calorimeter but also to the noise term. Crystals are accepted if their LY is higher than 7.2 pe/MeV when measured at 18^oC, with a photomultiplier Philips XP2262B in optical contact with the large base of the crystal and the other surfaces wrapped with tyvek. This threshold value corresponds to around 4 pe/MeV when read with two APDs in the test beam. The required precision on the LY measurement is of the order of a few percent. For what concerns the LY measurement, both centers use a radioactive source to excite the scintillating light, driven by a motor to move the source along the crystal. The measurements, one per cm along the crystal axis, take place in a dark room and care has been taken to eliminate any possible spurious light source. The light signal itself is quite small, since the available radioactive sources with a long lifetime produce γ rays of energies around 1 MeV and $PbWO_4$ crystals have a rather low LY.

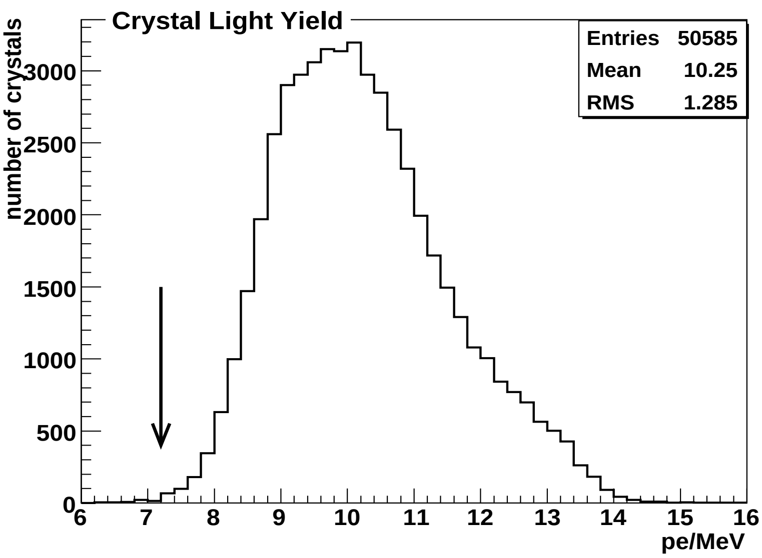

Figure 3: Light Yield measurements distribution; the arrow shows the acceptance cut.

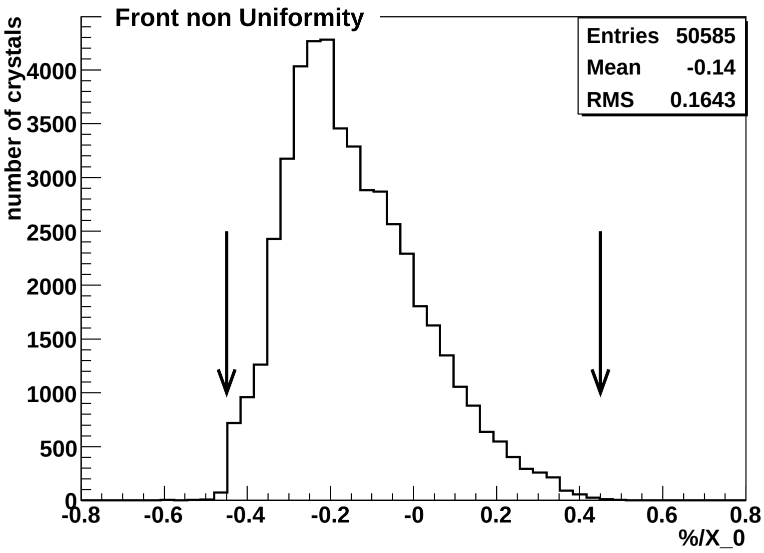

Figure 4: Front non-uniformity measurements distribution; the arrows show the acceptance cuts.

The tapered shape of crystals, required to obtain an hermetic pointing geometry, induces a focusing effect in the light collection. The same amount of energy deposited far or near the photo-detector will produce a higher or lower signal respectively. The uniformity of the light collection can be controlled by de-polishing with a given roughness one lateral face of the crystal. The ideal situation is to have a uniform light collection in the region of the maximum of the electromagnetic shower energy deposition. Due to the fact that the shower maximum position fluctuates, deviations from uniformity in this region will produce additional contribution to the constant term of the energy resolution. To maintain this contribution below 0.3% the maximum allowed deviation from uniformity in the crystal region 3 X_0 to 13 X_0 (front non-uniformity) was set to:

$$\frac{1}{LY}\frac{dLY}{dX} = \pm\, 0.45\%/X_0 \tag{1}$$

The LY and front non-uniformity distributions of Russian crystals are shown in Figures 3 and 4.

5 Precalibration

In the recent past, a strong correlation between the crystal light yield and their longitudinal transmission in the range of 350-370 nm has been noticed on a sample of around 6000 crystals in Rome Regional Center [6]. This correlation, verified on CERN data as well, is shown in Figure 5 on the full sample of 50000 Russian crystals measured up to now. The correlation factor between LY and LT360 is 77.3%. On the contrary there is no correlation between the LY and the transmission at 420 nm and 620 nm.

It is worthwhile to note that, assuming a simple model in which the emission spectrum is the same for all crystals and considering only the variation in the transmission spectrum, the maximum LY variation is expected to be below 10%, being the observed variation larger than 50% (Figure 5). This fact indicates that, in these $PbWO_4$ crystals, beside the natural correlation existing between light collection and absorption, there should be also a correlation between the amount of light produced and the transmission curve edge. This correlation might be due to a variation of absorption and emission center concentration from one crystal to another with consequent different positions of the crystal transmission band-edge and correspondingly different amount of light produced.

Exploiting the observed correlation, the transmission measurement can be combined with the direct light yield determination to improve the intercalibration of the crystals. LY best estimation comes from the average between direct LY and LY obtained from LT360 using the fit shown in Figure 5. This has been verified with calibration from CERN-SPS test beam. The agreement between this laboratory “best” intercalibration and the test beam intercalibration with electrons of 120 GeV is at level of 4% as shown in Figure 6; this is an excellent result considering the five orders of magnitude in energy between the MeV scale of the laboratory source and the electron energy in the test beam.

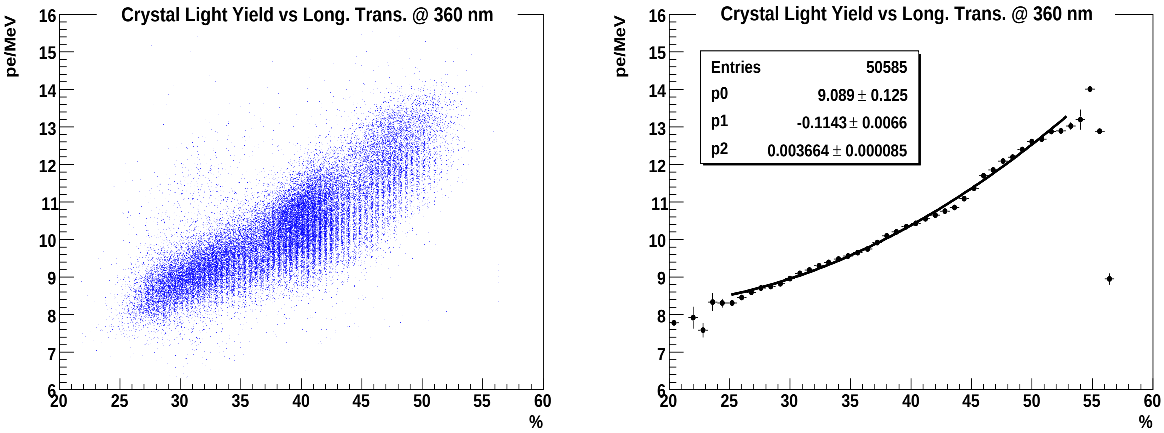

Figure 5: Light Yield vs Longitudinal Transmission at 360 nm; the profile on the right is fitted by a second order polynomial function.

6 Conclusions

The CMS electromagnetic calorimeter is a challenging project. After an extended R&D effort, the ECAL barrel construction is in the final phase in CERN and Rome Regional Centers while the endcap construction is starting now. Crystal properties are monitored in the ECAL Regional Centers continuously. The crystal light output is very uniform thanks to the precise depolishing of one lateral face; this contributes to reach the foreseen energy resolution. A very interesting correlation between Light Yield and Longitudinal Transmission is observed. This correlation provides an additional and independent measurement of the crystal LY, leading to a LY resolution improvement and to a 4% intercalibration precision of the calorimeter .

7 Acknowledgments

My acknowledgments go to E. Auffray, F. Cavallari and I. Dafinei for the precious help in collecting data from Cern and Rome Regional Centers.

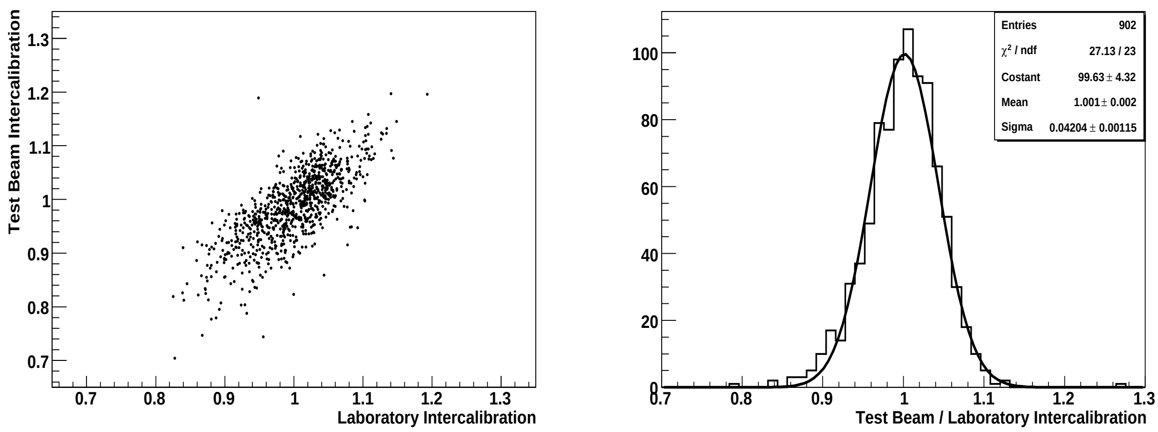

Figure 6: Comparison between the intercalibration coefficient obtained from CERN-SPS test beam with 120 GeV electrons and from laboratory measurements. On the right, the ratio distribution is fitted with a gaussian function.

References

[1] CMS Collaboration, “The CMS Technical Proposal”, CERN/LHCC 94-38, 1994.

[2] CMS Collaboration, “The CMS Electromagnetic Calorimeter Technical Design Report”, CERN/LHCC 97-33, 1997.

[3] A. A. Annenkov, M. V. Korzhik, and P. Lecoq, “Lead tungstate scintillation material”, Nucl. Instr. & Methods A 490 (2002) 30
R. Y. Zhu, “Radiation damage in scintillating crystals”, Nucl. Instr. & Methods A 413 (1998) 297.

[4] S.Baccaro et al. , “An automatic device for the quality control of large-scale crystal’s production”, Nucl. Instr. & Methods A 459 (2001) 278.

[5] E. Auffray et al. , “Performance of ACCOS, an automatic crystal quality control system for the PWO crystals of the CMS calorimeter”, Nucl. Instr. & Methods A 456 (2001) 325.

[6] L.M. Barone et al. , “Precise measurements of light yield and transmission of $PbWO_4$ crystals at the INFN-ENEA regional centre.”, Nucl. Instr. & Methods A 562 (2006) 76